Shipboard Microgrids

Maritime Islanded Power Systems Technologies

Guerrero, Josep M.; Jin, Zheming; Liu, Wenzhao; Othman, Muzaidi B.; Savaghebi, Mehdi; Anvari-Moghaddam, Amjad; Meng, Lexuan; Vasquez, Juan C.

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Shipboard Microgrids: Maritime Islanded Power Systems Technologies

Josep M. Guerrero, Zheming Jin, Wenzhao Liu, Muzaidi B. Othman, Mehdi Savaghebi, Amjad Anvari-Moghaddam, Lexuan Meng, and Juan C. Vasquez
Department of Energy Technology, Aalborg University, Denmark, www.microgrids.et.aau.dk
{joz, zhe, wzl, mum, mes, aam, lme, juq}@et.aau.dk

Abstract

The development of electrical power systems in maritime applications like ships, ferries, vessels and seaports are calling for more advanced technologies integrating power electronics, energy storage devices, control and supervisory systems and onboard communications. The challenges of those electrical isolated systems are being solved in other terrestrial microgrid applications, so that many ideas and concepts can be shifted and adapted in order to reduce the fuel consumption in marine applications. Compared with terrestrial microgrid applications, the concept of AC and DC SMGs are presented in this paper. Several relevant technologies and standards are provided to ensure adequate power quality and fuel efficiency in ship systems. However, there are still technological challenges and de-risking studies related to the control, protection and management of the system to be performed yet.

1. Introduction

The electrification of ships has been started from the early 20th century. In the following century, shipboard power systems (SPSs) have evolved greatly in both size and power level. Recently, due to the soaring prices of fossil fuels as well as the ever stricter regulation of emission from the government and international organizations (i.e. IMO), the concept of all-electric ships that employs electric propulsion systems and integrated power systems (IPSs) has drawn great attention from worldwide shipbuilding industry [1]. In recent studies, there has been an increasing interest to integrate energy storage systems (ESSs) and renewable energy sources (RES) into SPSs for reduction of sailing cost, thus making such a system more and more consist with microgrids. In this context, the IPSs can be defined as shipboard microgrids (SMGs), in which shipboard power sources and electrical loads (both electric propulsion power and ship-service loads) are considered and organized as an entity.

According to the type of distribution system, IPSs can be categorized as either DC distribution based or AC distribution based, in another word AC shipboard microgrids (AC SMGs) or DC shipboard microgrids (DC SMGs). AC SMGs can be traced back to 1986, when full electrical propulsion system was installed onboard *Queen Elizabeth II* [1]. During the following decades, more and more vessles installed AC SMG and started sailing, thus making AC SMG the mainstream type of existing SPSs. Compared with conventional ships, AC SMG enhanced fuel economy and continuity of power supply. However, the presence of high-power and/or non-linear propulsion loads in the vessels' power distribution systems induces a lot of power quality issues such as unbalanced voltage/currents, frequency deviations, active and reactive power oscillations and harmonic currents, etc. which can lead to potential risks. In the case of three-phase AC SMGs, the unbalanced grid voltage caused by short-circuit bought serious active and reactive power fluctuations at specific frequency among parallel synchronous generators [2]. During the start-up and brake of sailing, severe grid voltage and frequency fluctuation caused by substantial rapid load changing may result in power system eventually blacks out. The problem is even more critical along with the extensive use of emerging pulsed loads [3]. The application of large capacity power electronic converters based on switching actions may lead to larger harmonic currents injected into the power system that may cause sever voltage harmonics due to the relatively higher network impedance [4]. Furthermore, high-amplitude harmonic currents not only cause energy waste but also EMC and other power quality problems [5]-[14].

On the other hand, although overwhelming majority of existing AESs are using AC power architectures, the recent advances in power electronics are giving rise to a tendency toward DC distribution systems [15]. With existing AC power architectures, the speed of each generator has to be adjusted in order to maintain the systemic frequency (i.e. 50/60 Hz), irrespective of the load conditions. This results in a sub-optimal usage of the prime movers and the inability to further modify the fuel efficiency. Moreover, thanks to the rapid development of modern power electronic technologies, high-frequency dc-dc converter has already qualified for taking on the role of transformers in DC systems. The driving force for this transition lies on one hand in the challenges associated with the conventional AC power architectures [16], and the increasing interest in integration of emerging energy sources and storage devices with DC output (e.g. fuelcell, flywheel or battery) [17]. For commercial cargo ships, application of DC power architecture with higher fuel efficiency and potential reduction in volume and weight lead to better fuel economy and increased payload. As for naval vessels, the research and development activities are motivated by significant enhancement in survivability [18] and the emerging need for supporting high-power electrokinetic weapons with high-power pulsed load characteristic [19].

To address these shipboard power concerns associated within acceptable levels on shipboard, several maritime standards provided the recommended practices for defining, measuring, quantifying and interpreting electromagnetic disturbances, and relevant ship power quality control methods were continuously put forward to ensure adequate quality and reliability in SMGs [6]-[14].

2. AC Shipboard Microgrids

2.1. Ship AC Maritime Microgrids Model and Droop Isochronous controls

Traditional AC SMG features integrated power systems (IPS) model can be simplified as shown in Fig.1. The model consists of multiple parallel generators which can realize the fault ride through control under sever unbalanced and harmonic ship grid voltage. The main switchboards installed at the point of common coupling (PCC) are physically separated to each other as well as the circuit breakers to improve the survivability and redundancy. Furthermore, two or more propulsion systems can be provided to ensure the continuous power supplied to the propulsion motors.

Considering the distributed power flow onboard, droop control [6] is an interesting technique choice for parallel inverters synchronization without intercommunication lines. The typical applications of the droop methods are for distributed power generations operating in grid-connected or islanded modes [5] which can also be used into shipboard microgrids systems. Nevertheless, the droop controller must be reformulated taking into account suitable virtual impedances to avoid the circulating distorted currents and balance active and reactive power when sharing nonlinear loads [6].

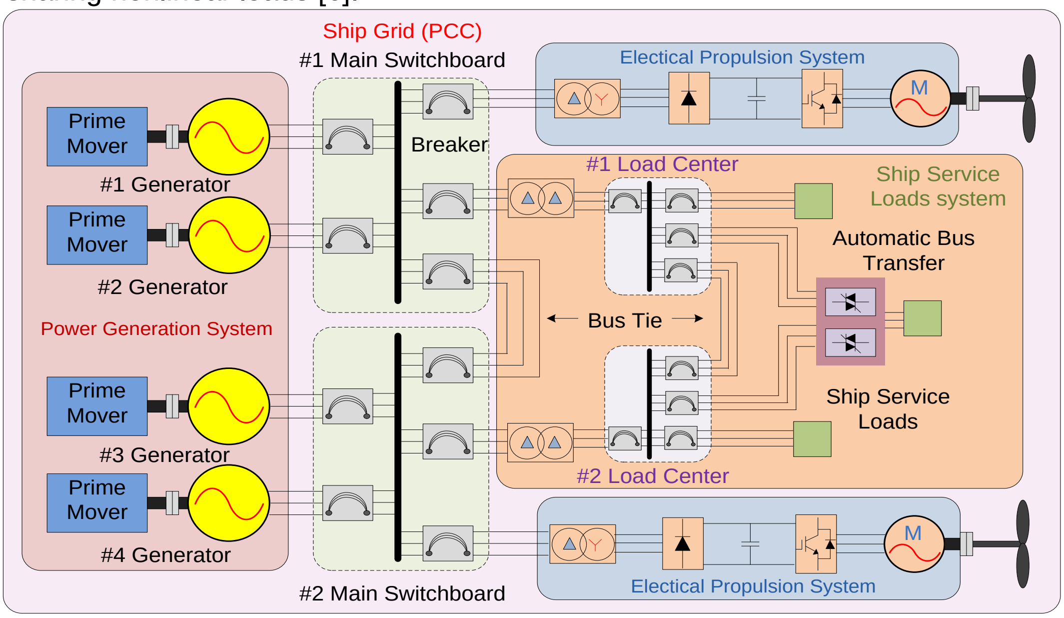


Fig. 1. Model of AC Shipboard Microgrids

On the other hand, since the load-dependent frequency deviation characteristic of droop method, it implies a phase deviation between the output voltage frequency of the power supply system and the input voltage supplied by the utility mains. This fact can lead to synchronization losses but can be applied to SMGs because the bypass switch can connect directly to the utility line directly to the SMG bus [7].

2.2. Power Quality standards for ships

The limits for voltage and frequency fluctuation and harmonic distortion are defined by several maritime standards to ensure the reliability of power electronic equipment and the safety of crews on shipboard. Most general standards such as the IEC60092-101 [8], Lloyd's Register Standard [9], Military Agency Standardization for navy STANAG1008 [10], American Bureau of shipping (ABS) 2008 [11], and the IEEE Coordinating Committee Standard 45-2002 [12], imposed a lot of peculiar voltage and frequency requirements that must be respected in the shipboard integrated power supply systems. The detailed permission levels of voltage and frequency variations and harmonic distortion can be found in Table I. However, the Det Norske Veritas (DNV) standard defines more severe limits for permanent voltage variations of $\pm 2.5\%$ and $+20\%, -15\%(s)$ for short duration variations, and up to 10% THD limit are allowed for dedicated systems such as the propulsion switchboards [13].

TABLE I. PERMITTED LEVELS OF VOLTAGE AND FREQUENCY DEVIATIONS FOR SHIP POWER SUPPLY SYSTEMS

Standards	Instruments and Parameter Variations				
	Range of The Standard	Voltage	Frequency	Total Harmonic Distortion	Individual Harmonic Distortion
Polish Register IEC60092-101	Electrical Installations in ships. Definitions and general requirements	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$5\%(40\,th)$	3%
Lloyd's Register	Selection and Use of Standards for Naval Ship	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$8\%(50\,th)$	1.5%
STANAG1008	Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition9, 2004	$\pm 5\%$ $\pm 16\%(2s)$	$\pm 3\%$ $\pm 4\%(2s)$	$5\%(40\,th)$	3%
American Bureau of shipping 2008	Rules of International Ship Classification Societies, eg PRS/25/P/2006	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$5\%(40\,th)$	3%
IEEE Std.45-2002	IEEE Recommended Practice for Electrical Installations in ships	$\pm 5\%$ $\pm 16\%(2s)$	$\pm 3\%$ $\pm 4\%(2s)$	$5\%(40\,th)$	3%

2.3. Power Quality Enhancement in AC Shipboard Microgrids

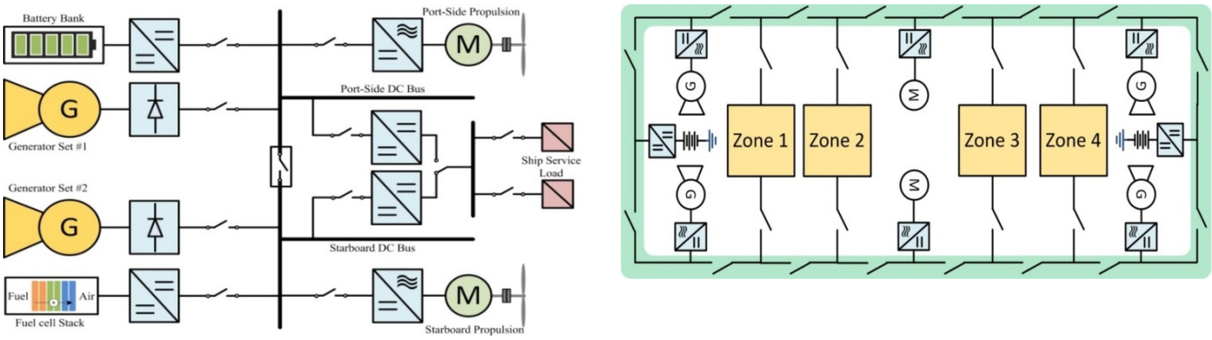
AC SMG power quality improvements based on compensation control are widely introduced according the current technologies. Power quality improvement mainly involves the reduction in deviation of voltage/ frequency fluctuation, unbalanced and harmonic waveform mitigation in AC Maritime Microgrids In general, the principle of power quality compensation control is to extract the non-ideal signal from the polluted source side to generate compensation reference component. However, the core elements to accomplish the power quality control need diverse power electronic devices based various control solutions because of the fast dynamic demands under more challenging ship circumstance [14].

Currently, power compensators such as fixed capacitor (FC), static var compensators (SVC), and static synchronous compensators (STATCOM) not only reduce unbalanced ship grid voltage fluctuations but also realize power harmonic suppression. Passive or active power filters have become an effective way to reduce the harmonic flow and make a satisfactory performance in the power supply systems. Further, the solid state transfer switch (SSTS) can realize the fast recovery of voltage sags by eliminating negative sequence components. Uninterruptable power supply (UPS) can restrain voltage and frequency transient disturbance. In addition, the dynamic voltage regulator (DVR) and unified power quality controller (UPQC) can directly compensate the instantaneous current harmonics in the power systems.

3. DC Shipboard Microgrids

3.1. DC Power Architectures

Notional power architectures of DC SMGs are shown in Fig. 2. In these architectures, the need for AC/DC rectification will decouple generators from each other, thus each generator set can operate optimally in their most efficient points, which will lead to significant fuel efficiency improvement. At the same time, several problems associated with AC distribution such as reactive power flow and harmonic problems can be eliminated. In addition, the elimination of synchronization makes parallel connection and disconnection much easier in DC system, thus allowing "plug and play" and reconfigurable structure such as DC zonal electrical distribution system (ZEDS) that is designed for naval medium-voltage DC power systems [18].



(a) (b)

Fig. 2. Diagram overview of shipboard DC power system: (a) typical structure, (b) DC ZEDS.

3.2. Onboard Energy Storage Systems

In case of maritime applications, onboard ESSs are taking on a pivotal role in the IPS of next-generation AES. For naval applications, the main reasons for ESS are twofold: (1) to enhance survivability; (2) To enable high energy pulsed loads [19]. Without ESS, the shipboard generators would be significantly oversized in order to support the high energy pulsed nature of electric weapons. Even with ESS, the growth of auxiliary loads and the capacity needed to support electric propulsion necessitates a capability to utilize reserve capacity of online generators and ESS in order to "deliver the right amount of power to the right place in the ship at the right time"—which is enabled by DC SMGs.

As for the commercial sector, the fuel economy is a major concern, considering the fact that diesel generation is still the major power source of all maritime applications, its efficiency characteristic in fixed-speed operation is as shown in Fig. 3. In general, engineers will intentionally design and make the diesel generator sets work in their high-efficiency area and modulate the number (*K* in Fig. 3) of running engines in order to achieve optimal load matching. However, instantaneous fluctuations in demand side (e.g. dynamic positioning) will break the balance between power generation and power consumption, and thus reducing the fuel efficiency. The presence of the ESSs can inject bi-directional controllable power flow into the system to achieve load conditioning; such a fact enables modifying fuel efficiency with the help of onboard ESSs. In this way, it is possible for diesel generator sets to work constantly with its modified fuel efficiency.

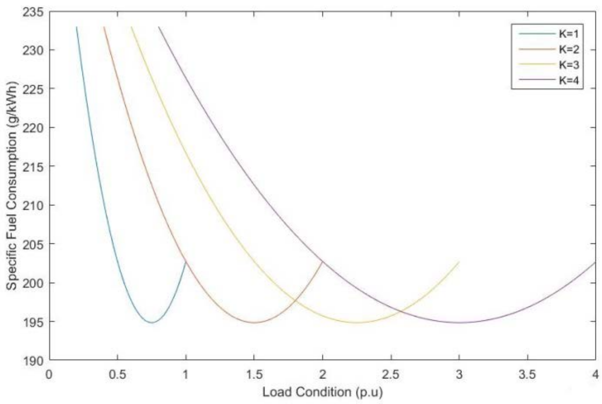


Fig. 3. Fuel efficiency characteristic of diesel generation (in fixed-speed operation).

3.3. Hierarchical Control

Despite the benefits offered by DC SMG, voltage regulation is still a challenging task in vessel's highly dynamic load conditions, especially in dynamic positioning operation, and real-time single-target or multi-objective optimization at the same time. A potential solution for this challenge can be employing hierarchical control scheme from terrestrial microgrids [6]. In hierarchical control scheme, the microgrid can be controlled with several control layers as shown in Fig. 4. The control strategy is preferred because it introduces independent behaviors between different control layers, thus optimization functions and stabilization of the power system can be achieved at the same time, especially for isolated ones with finite generation and inertia.

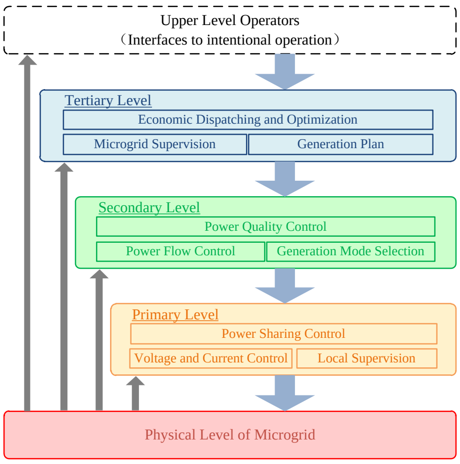


Fig. 4. Different control layers in hierarchical control.

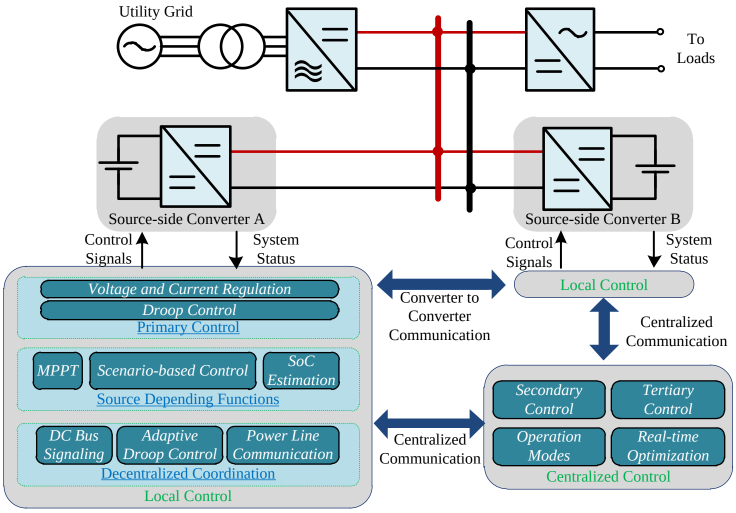


Fig. 5. Implementation of hierarchical control in practical DC microgrid.

Fig. 5 shows the typical control architecture applying hierarchical control in a generalized DC MG. Droop control can be installed as the primary control method for active power sharing purpose. The droop coefficient can be regarded as a virtual internal resistance, in this case, the droop control consists with the physical connection of dc sources and it therefore simplified the design of the parallel converter systems in the dc microgrid. A small voltage deviation will be introduced by droop based primary control, thus, secondary control is introduced to compensate the voltage deviation. In most cases, straightforward PI controller can be employed to meet the need of tracking nominal voltage reference. However, adaptive droop control that uses adaptively changing droop coefficients instead of fixed droop coefficients has also been introduced to some high requirement systems using decentralized coordination. It differs from primary and secondary control, in that the tertiary control is providing optimization functions, thus, not only the controller itself but also decision making methods have been proposed to achieve specific optimization objectives.

3.4. Protective Functions

The protection of SMGs, especially those with complex reconfigurable configuration, is a challenging task requiring the development of solid state circuit breakers (SSCBs) and complex coordination between power converters and protective functions [21]. Comparing with conventional transformers, instantaneous over-current capability of power electronic converters must be limited in order to avoid equipment damage whereas conventional transformers inherently carry reserve inertia to sudden electrical transient events. Also, considering DC ZEDS, since zones are normally interconnected, there may be scenarios where a single failure may spread and upgrade into regional failure or systemic crash if the protective architecture is not designed to address the potential for such scenarios. Hence, effective fault protection and fault-point isolation are considered as the major challenges for ensuring the safety and reliability of DC SMGs.

The reconfiguration capability is one of the most promising advantages of DC SMGs for future AES, especially for naval applications [20]. However, the non-linear multi-connectivity and high-dimensionality of the onboard power system make it difficult to achieve fast and efficient reconfiguration. Returning to the DC ZEDS discussion related to Fig. 2, several advanced concepts have been introduced to address the protection dilemma. An essential approach is the self-healing reconstruction method, which firstly sub-divides the power system into several zonal microgrids and then reconstructs from microgrids when faults are cleared. The sectionalizing aims at the minimization of the isolated area and maintaining the power supply to healthy zones at the same time. Further, the sectionalized zonal microgrids will attempt to connect with each other and form networked microgrids, which can improve the operation and the reliability. In this way, the power system will recover from a fault in several steps and isolate the fault location at the same time.

4. Power and Energy Management Systems in Maritime Microgrids

On this part, Power and Energy Management System (PMS and EMS) in SMG concepts are illustrated in Fig. 6. In this context, the research outcomes from the field of microgrids, especially power and energy management methods, is compatible with shipboard power system. In contrast with the terrestrial power system, the SMG need to consider several constraints which differ from the terrestrial microgrids and cannot be applied directly [21].

The load demand in the SMG is dominated by the high penetration of propulsion loads which is very dynamic depending on the variation of speed. The rated load demand of the propulsion operation can take up to 90% of the whole power capacity of the power generated [22]. However, also there are off-shore support vessels that are designed as maritime mobile power plants. For these vessels, generators are not designed to feed propulsion power demands. Moreover, some particular loads in naval ship draw very high power for very short periods (in second or millisecond level) of time such as called Electromagnetic Aircraft Launching System (EMALS), electromagnetic weapons and free electron lasers [23]. Such loads are called pulse loads or also known as pulse power loads (PPLs), which may attempt the system stability [24][25]. Thus in the next 25 years, especially in naval aircraft carriers these new electric loads will surpass the propulsion load and the generation of these ships can exceed 100MW to cater the load requirements [26]. In addition, non-linear loads can also contribute to the reduction of stability margin to the system [27]. Consequently, this situation will affect the generator power and other loads effectiveness and reliability. As the emerging of multipurpose storage system, the so called ‘energy magazine’ (container of bullets) was introduced to cater the pulse load power demand [28]. However, the system is not matured yet to be applied in this area.

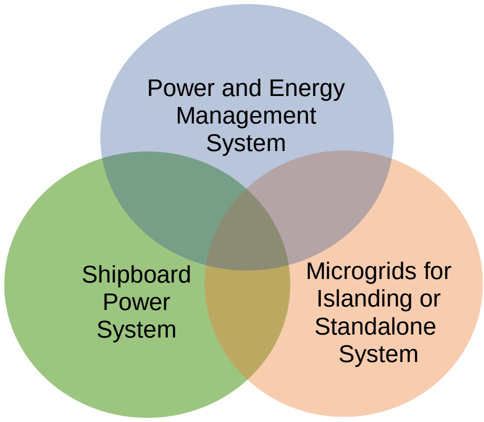


Figure 6: Field of study

In designing the management and optimization strategy for PMS of the SPS, optimality and security are two important issues. Moreover, the constraint of the generation capacity and load demand in any case of study, redundancy of the system to allow reconfiguration technics [29] of the power grid system and dynamic loads studies are the things to be considered. In AC and DC ZEDS, the priority of the load shedding in the SPS is classified whether it is vital loads, semi-vital loads and non-vital load. This is to ensure the non-vital loads will be shed first when the load demand exceeded the generation capacity [27]. Under security constraint of PMS [21], the operation of SPS is running in optimal while keeping the system secured. In doing this, additional function is needed to control the generated power, bus voltage, active and reactive power flows through the network, status of the system loads, configuration of the system, and so on.

5. Conclusions and Future Trends in Shipboard Microgrids

The AC maritime microgrids part have reviewed the ship AC maritime microgrids model and introduce the droop isochronous control for distributed parallel generators first. After that, power quality issues in ships and the most relevant maritime standards are comprehensively discussed. Finally, a variety of power quality control methods with diverse power electronic devices are briefly investigated for ship power supply systems

On the other hand, Presently, DC SMG has become one of the major directions of research and development activities in shipbuilding industry. In the past decade, there have been several prototypes applying DC power architecture in low-voltage DC level developed by companies like ABB. Also, medium-voltage DC level power architectures have been designed and implemented in the new surface combatant developed by U.S. Navy. Yet, there are still technological challenges and de-risking studies related to the control and protection of the system to be performed. With the advanced control and management methods from terrestrial microgrids, it is foreseeable that DC MMG will be promising solution for the efficient and reliable power system of future AES.

Power and energy management or the higher level of control in the SPS is important, mostly for the AES in order to operate in secure and reliable state. Moreover, the SPS needs to work optimally with the finite power generation in satisfying operating constraints as well as to serve the pulse load.

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